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SPACECRAFT ELECTRICAL CONNECTOR SELECTION AND APPLICATION PROCESSES

An overview of an internal assessment of NASA's processes on electrical connector selection and application as well as derived lessons learned.

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Abstract -- This assessment was initiated by the NASA Engineering & Safety Center (NESC) after a number of recent "high profile" connector problems, the most visible and publicized of these being the problem with the Space Shuttle's Engine Cut-Off System cryogenic feed-thru connector. The NESC commissioned a review of NASA's connector selection and application processes for space flight applications, including how lessons learned and past problem records are fed back into the processes to avoid recurring issues. Team members were primarily from the various NASA Centers and included connector and electrical parts specialists.

The commissioned study was conducted on spacecraft connector selection and application processes at NASA Centers. The team also compared the NASA spacecraft connector selection and application process to the military process, identified recent high profile connector failures, and analyzed problem report data looking for trends and common occurrences.

The team characterized NASA's connector problem experience into a list of top connector issues based on anecdotal evidence of a system's impact and commonality between Centers. These top issues are as follows, in no particular rank order: electrically shorted, bent and/or recessed contact pins, contact pin/socket contamination leading to electrically open or intermittencies, connector plating corrosion or corrosion of connector components, low or inadequate contact pin retention forces, contact crimp failures, unmated connectors and mis-wiring due to workmanship errors during installation or maintenance, loose connectors due to manufacturing defects such as wavy washer and worn bayonet retention, damaged connector elastomeric seals and cryogenic connector failure.

A survey was also conducted of SAE Connector AE-8C1 committee members regarding their experience relative to the NASA concerns on connectors. The most common responses in order of occurrence were contact retention, plating issues, worn-out or damaged coupling mechanisms, bent pins, contact crimp barrel cracking and torn seals. In addition to these common themes, responses included issues with markings, dimensional errors on the build, contact/socket damage (handling), manufacturing defects and customer misapplication and mishandling.

The NESC team concluded that considering the large quantity and wide variety of connectors successfully flown on human and robotic space applications, the number of failures is quite low. However, "high profile" failures with significant cost, schedule, safety, and/or mission success impacts continue to occur. It was also concluded that connector failures occur throughout a system's life-cycle with the majority of connector issues application related. A number of recommendations were

identified for improving NASA connector selection processes and overall space connector reliability and performance.

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I. INTRODUCTION

This assessment was sponsored by the NASA Engineering & Safety Center (NESC). The NESC is an independently funded organization that provides objective engineering and safety assessments to NASA and collaborating organizations that support space based systems. This also includes conducting proactive investigations to identify and address potential concerns before they become major problems.

Several factors led the NESC to commission an electrical space connector selection and lesson learned assessment. Initially, a NASA managed program developed out-of-specification connector bonding resistances which were attributed to using electroless nickel plated aluminum electrical connectors. NASA has also recently experienced a number of "high profile" connector problems, the most visible and publicized of these being the problem with the Space Shuttle's external tank Main Engine Cut-Off System

and specifically its cryogenic feed-thru connector which resulted in several cancelled launch attempts. This pointed to the need for a broader NESC review of the electrical connector selection and application processes for space flight applications, and how lessons learned and past problem records are incorporated to minimize the potential for recurrences.

The objectives of this study were to review the space connector selection and application process, including the roles and responsibilities of government, contractors and subcontractors, the requirements approach, and to determine how lessons learned are incorporated. The intended goals are to determine if there is potential to improve NASA in the above areas either by direct NESC involvement or indirectly via recommendations to the NASA Office of Chief Engineers. A secondary and important goal is to disseminate findings and recommendations to the aerospace community.

NESC team members who conducted the assessment were connector and electrical parts experts from the various NASA Centers and representatives from aerospace industry. Findings and recommendations of this project were provided to the NASA Office of Chief Engineers in an NESC published report entitled "Spacecraft Electrical Connector Selection and Application Process," NESC Request No: 08-00481. The full report can be obtained from the NESC. This paper provides a summary of the NESC report.

II. PRESENTING ISSUE

This assessment was initiated after a NASA managed program developed out-of-specification bonding resistances attributed to using electroless nickel plated aluminum connectors. Gold-plated electrical connectors have typically been used in spacecraft applications to establish a low impedance contact with hardware chassis wire harness and Electromagnetic Interference (EMI) shielding. Connectors with electroless nickel plating have been widely used for many years. EMI bonding and grounding requirements typically define a maximum allowable resistance for the connector housing to wire harness shield or connector housing to chassis connection, as appropriate. Connector manufacturers use a variety of coatings/plating systems and processes to create a protective and highly conductive surface on the aluminum connector shell.

Most space grade connectors are made of an aluminum alloy. Aluminum is a reactive metal with good corrosion resistance since it quickly forms a passivating oxide layer¹. The protective oxide is non-conductive. A conductive plating system is added to the aluminum surface so a low resistance electrical bond can be maintained between connector faying surfaces. A low resistance value of 2.5 milliohms or less is typically required to maintain acceptable connector electrical shielding and EMI requirements (i.e., MIL-C-38999,

paragraph 3.29 series 3 aluminum connectors). Common plating systems for space applications are gold and nickel. Both plating systems can provide good surface conductivity, but nickel provides limited corrosion protection compared to gold. Nickel is cathodic to aluminum and therefore, corrosion protection is accomplished by encapsulation of the substrate. As long as the nickel plating remains intact and the aluminum substrate is not exposed, substrate corrosion will not be an issue. Once the aluminum is exposed, the connector can be corroded in a moist environment. This results in a resistive coating that degrades EMI and electrical shielding/bonding properties.

Electroless nickel plating systems are particularly susceptible to porosity and can be physically damaged (scratched) during connector installation and handling. In aviation, this has been a serious issue, leading military services to restrict electroless nickel aluminum connector usage (i.e., MIL-STD-1568, paragraph 5.10.3.5) during the 1988-89 timeframe. The primary issue was corrosion which caused connector damage on aircraft as a result of exposure to high humidity and salt water and/or due to handling-induced plating damage. This prohibition did not apply for spacecraft applications. For many years, the United States military and commercial aviation solution for aluminum connectors has been an electroplated nickel with a cadmium and chromate conversion coating. Cadmium and chromate act as sacrificial coatings and protect the aluminum substrate when the connector plating system is physically damaged. This system is not used for space applications since there is a concern with cadmium outgassing in space/vacuum environments. Recent environmental restrictions on cadmium and chromate use have resulted in new corrosion resistant plating systems being developed that meet electrical bonding and EMI shielding requirements. These new aluminum connector plating systems and plated composite connectors have been added to the most recent version of MIL-C-38999.

In spacecraft applications, the consequences (e.g., risks) for these bonding resistance problems vary considerably. If connector bonding resistance exceeds the system requirement by less than an order of magnitude and appears stable, then a waiver typically is generated. Major risks could occur when the bonding resistance continues to increase over time, including electromagnetic emissions coupling to surrounding signals, or corrosion products on electrical contacts potentially creating electrical open circuits or high resistances. These more serious conditions have been observed when electroless nickel aluminum connectors are physically damaged or are stored with certain types of Ethylene-TetraFluoroEthylene (ETFE) wire insulation which can lead to corrosion. This is documented in the Government-Industry Data Exchange Program (GIDEP) Alert EA-P-98-02B "Wire Outgassing" issued in 1992 and NASA Goddard Advisory, NA-GSFC-2003-03 "Fluoropolymer Degradation Resulting in Corrosion of Packaged Pre-wired Connector Assemblies" issued in 2003

(downloadable at <http://nepp.nasa.gov/npsl/wire/NA-GSFC-2003-03.pdf>).

Electroless nickel coated aluminum connectors should not be used in areas exposed to humidity and salt water. Use should also be restricted in high maintenance areas where the nickel plating can be damaged, exposing the aluminum and leading to corrosion. As noted above, these connectors should also not be stored with fluorinated wire insulations known to outgas reactive fluorine.

Electroless nickel connectors can perform well in space applications with appropriate cautions. An example is the International Space Station (ISS) which has a large number of electroless nickel connectors and has not experienced significant connector issues. Gold-plated aluminum connectors with a nickel barrier should be used when there are stringent EMI shielding requirements. Electroless nickel aluminum connector performance and specifically corrosion resistance can be improved by using enhanced manufacturing processes and the following handling guidelines:

- Minimize surface roughness of the aluminum shell and clean surface prior to plating to promote good plating adhesion and reduce porosity.
- Increase phosphorus content in the electroless nickel plating solution to hardness plating. Insure that other proprieties such as conductivity and porosity are not adversely affected.
- Eliminate plating bath contaminants and replace aged solutions which will promote better corrosion resistance and plating adhesion.
- Increase plating thickness, however, ensures that excessive plating does not create an adhesion issue.
- Maintain connectors in a low moisture and non-corrosive environment during storage, installation and in operational use.
- Use suitable type gloves when handling connectors.
- Avoid damaging plating and exposing the aluminum substrate during storage, installation and operational use.
- Inspect and replace or repair connectors with damaged plating during repair and modification procedures.

Connector Selection Process

Central to the electrical system of human and robotic spacecraft and launch vehicles is the wiring harness with electrical connectors that mate to various avionics boxes and interface panels as required by the overall electrical system design architecture. Inside avionics boxes circuit card assemblies may also interface to backplanes through blind mate card connectors. Specialized high voltage, radio frequency, ribbon cable, fiber optic, etc. connectors have

found use in flight applications. Spacecraft and launch vehicles interface to ground processing facilities typically through umbilical connectors that de-mate prior to or during the launch sequence. The spacecraft electrical connector selection and application process and how field use experience feeds back into this process was the main focus of this assessment.

Electrical connectors may be selected by an avionics box lead, mechanical design engineer, electrical design engineer, harness engineer, or system engineer, as will be described in more detail in subsequent sections. Additionally, a connector may be selected by a supplier during interface definition or even by default in case of an existing system built for previous missions. Factors such as hermeticity, shock and vibration tolerance, vacuum compatibility, out gassing and/or contamination, magnetic properties, EMI performance, size and weight, current and/or voltage capability, cost, and availability, are considerations for selection depending on the application. Connector choice can clearly impact multiple engineering disciplines through the entire mission life-cycle.

The ideal spacecraft electrical connector selection and application process should have a “control system”-like feedback mechanism implemented to build upon anomalies experienced in field use and increased knowledge as shown in Figure 1.

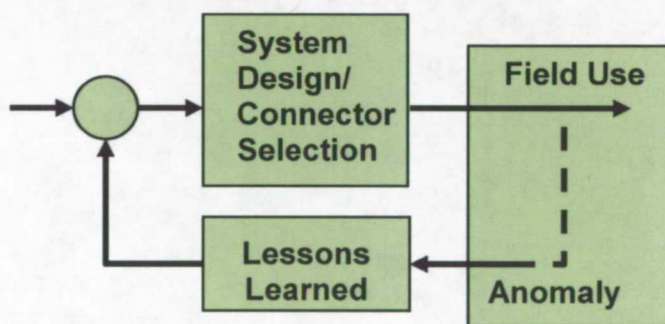


Figure 1. Idealized electrical connector selection and application process

However, upon review, the current NASA process followed the more nebulous route below in Figure 2.

Typically an anomaly is discovered by a project/program and the resulting investigation is funded by that specific project/program. The project/program investigates to a level of root cause understanding sufficient to meet the project/program's needs.

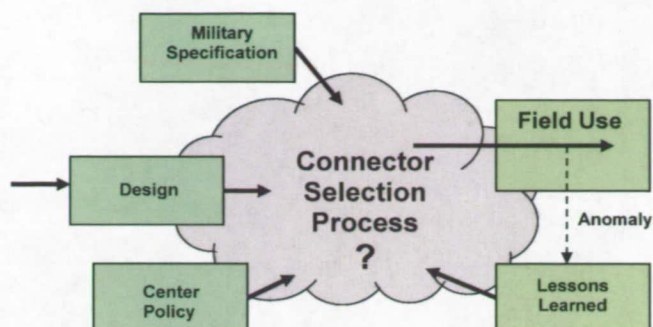


Figure 2. Actual NASA Connector Selection and Application Process

There is a perception that many designers regard connectors as a well-debugged commodity with minimal failure modes. In reality, agency experience has shown that a connector is a complex system having many failure modes. Safe and reliable use of a connector requires close attention to its design and implementation in each application and environment to avoid each of the many failure modes.

Most NASA missions produce one-of-a-kind or low volume space flight systems, although the Agency's Space Shuttle Orbiter and Solid Rocket Boosters (SRBs) are re-usable. Often spacecraft assembly and functional testing is performed in a "clean room" environment. Electrical connector mate and de-mate cycles are typically minimized, and logs of these mate and demate cycles may be maintained. Six NASA centers participated in this study, each with unique missions and in some cases different connector selection processes and methods of documenting and reporting connector failures. A listing of the participating NASA Centers and their mission with respect to connector selection and use is given in Table 1.

Table 1. Participating NASA Centers and Primary Mission

NASA Center	Primary Mission
Goddard Space Flight Center (GSFC)	Advanced instruments and spacecraft for Earth-orbiting and other space missions.
Johnson Space Center (JSC)	Design center for Space Shuttle, International Space Station and Orion program
Langley Research Center (LaRC)	Aviation and supersonic aircraft development and test facility for space systems
Kennedy Space Center (KSC)	Launch operations for NASA programs and maintenance facility for the space shuttle
Jet Propulsion Lab (JPL)	Develops and manages unmanned planetary and deep space systems

Marshal Space Center (MFSC)	Design center for propulsion and transportation systems such as the space shuttle and Ares rockets
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Review of Lessons Learned Databases

As part of this study, the GIDEP Advisories and Alerts system was queried for connector related issues. NASA directs its Centers and flows down the requirement to its contractors to routinely review and, when appropriate, submit GIDEP Alerts and advisories. NASA also maintains a public and limited access Lessons Learned data base and a NASA Advisory system.

The existing GIDEP (Government/Industry) process has multiple levels of reporting for parts and other problems:

- **Alert:** A GIDEP document that reports a problem with parts, components, materials, specifications, software, manufacturing processes, or test equipment that can cause a functional failure.
- **Problem Advisory:** A GIDEP document that reports a problem with parts, components, materials, manufacturing processes, specifications, software, manufacturing processes, or test equipment that has an unknown or low probability of causing problems for other users.
- **Agency Action Notice:** A GIDEP document that redistributes problem information issued by a Government Agency to GIDEP participants.
- **Safe-Alert:** A GIDEP document that reports a non-conforming item, product, or situation that creates a safety hazard for personnel or equipment

GIDEP databases, while beneficial, give only limited information and provide an incomplete picture of connector issues because manufacturers are often encouraged to write GIDEP Alerts on their own products. Consequently, these results often include positive "spins" and may omit details that could provide competitive advantages to other vendors. Also, NASA and many of its contractors use internal alert systems with restricted access so the information does not become widely known. NASA and its contractors are required to verify connector selection against GIDEP issues and submit issues to GIDEP; however submitting issues to GIDEP is not well enforced.

As part of this study a GIDEP record search on "connector" was performed for the years 2002 through 2008. Forty-five records were returned, including GIDEP Alerts, Problem Advisories, Agency Action Notices, and GIDEP Lessons Learned over the seven-year period. Two NASA Advisories were issued during that period. Trending indicated a decrease in the rate of GIDEP records issued per year; see the lower plot ("GIDEP") in Figure 3 below. NASA connector discrepancies (data among four Centers) attributed to

connector manufacturer causes (“NASA”) are trended in the upper plot of Figure 3. The difference between the slopes (0.76 and 0.83) is not significant, indicating similar reliability growth between “GIDEP” and NASA discrepancies. Thus, GIDEP records are, in fact, a representative “sample” of NASA connector occurrence rates. Trending results indicated nominal connector reliability improvement (growth) given the above assumptions.

The quantity of reported connector problems show that NASA and its contractors only report a fraction (less than 20%) of the problems encountered to GIDEP (see Figure 3 below). If other government users and contractor’s discrepancies were included in a similar analysis, GIDEP under-reporting would be much worse.

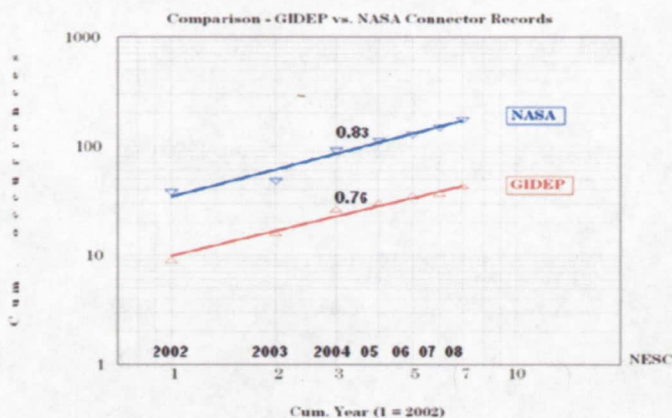


Figure 3. Connector GIDEP and NASA discrepancy trends for 2002 through 2008. Numbers above fit lines are slopes (β 's).

The Agency’s present Lessons Learned approach is documented in NPR 7120.6 “Lessons Learned Process” dated March 22, 2005. A search for the term “connector” was entered into the existing online Lessons Learned searchable database at: <http://nen.nasa.gov/portal/site/llis/LL/>. Forty-six records resulted, and a summary of the distribution of these reports is shown in Figure 4. The mate and de-mate condition (36% of write-ups) typically resulted in bent or recessed pins due to improper mating. Design issues in the form of misapplication or improper selection of the connector accounted for 23% of the write-ups. GSE accounted for 13% of the write-ups and primarily cited cases where arcing had occurred due to a short condition or high voltage. Crimps accounted for 8% of write-ups and dealt with a loose or inadequate crimp connection. Cryogenics accounted for 5% of the write-ups and cited a buildup of a dielectric film at cryogenic temperatures.

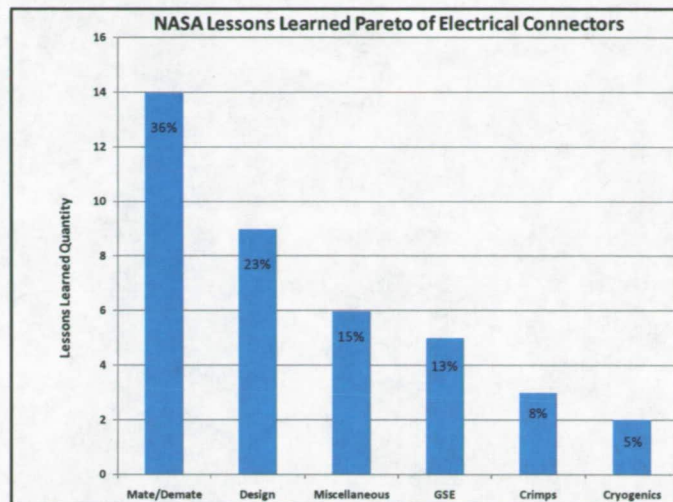


Figure 4. NASA Lessons Learned Pareto of Electrical Connectors.

A key aspect of this assessment was the evaluation of the mechanisms NASA uses to learn from its mistakes. During this assessment, the NESC team looked for processes that would capture connector-related issues in design, manufacturing, installation, and application. More importantly, once captured, the team looked for processes that would add information in the most efficient and accessible way, to the collective knowledge of those working with connector and wiring systems within the Agency and its partners (e.g., contractors and other organizations) nation and world-wide.

Review of NASA Center Connector Issues:

In order to assess connector selection and connector related failures participating NASA Centers were asked to discuss their connector selection and design processes and review their databases for connector related failures. A brief summary of representative Center reports follows:

GSFC Projects and Programs provide advanced instruments and spacecraft for Earth-orbiting and other space missions. Many GSFC spacecraft are Earth-observing, others perform “outward looking” scientific measurements, and some provide exploratory deep space systems. Typically, GSFC missions follow a concept-design-build (fabrication)-Integration and Test (I&T)-launch-operations phasing. Connector selection usually will occur early during the design phase and continue, along with procurements, during fabrication.

Nearly seven hundred connector-related faults and failures (including some wire/wiring and fiber optics) were reported from three different GSFC databases and another non-database/text source during 1999 - 2008. Most of the GSFC instruments and spacecraft are launched into Earth orbits or deep space; they are not subject to repair and maintenance (excepting the Hubble Space Telescope). Consequently,

most of the GSFC's connector-related faults and failures (~99%) occurred during ground processing prior to spacecraft launch. Only nine anomalies attributed to connectors occurred in operational phases ("on-orbit" or ground communications systems) and *none* resulted in mission failures.

Connector problems classified by failure mode showed 719 faults/failures among 605 connector events (some problems had more than one mode). Figure 5 presents these modes in a Pareto chart. The four left-most modes are associated with workmanship-induced defects and are grouped together; the remaining modes appear in the right hand grouping. Electrical high or low resistance connectors or contacts accounted for 1.8% and low pin retention force was 0.6%; neither is included in Figure 5. Faults or failures caused by process (failing to follow procedures or processes, improper paperwork) are not included in these failure mode counts.

Of the 83 electrical faults/failures (shorted, open, or high or low electrical resistance) 20% exhibited intermittent electrical signatures. Faults or failures caused by process (failing to follow procedures or processes, improper paperwork) are not included in these failure mode counts.



- 1- Missing or incorrect hardware 4- Incorrect Wiring
 6- Other OEM Workmanship 7- Assy Interference
 2- Damaged or failed 3- Loose 5- Not seated/mis-mated
 8- Broken wire/conn 9- Elec. Short 10- Corrosion/Contamination
 11- Elec. Open 12- Misaligned
 13- Bent pins/connector

Figure 5. Failure mode distribution of GSFC connector faults and failures. Four left hand bars are workmanship-related; right hand bars are other modes.

A separate classification by fault/failure cause (workmanship, design, process, connector manufacturer fault, or human factor) involved 696 records among the above-cited data sources. A Pareto chart for the GSFC connector faults/failures by cause is shown as Figure 6. The percentages in Figure 6 have been adjusted for unknown causes (i.e., those for which discrepancy causes could not be discerned from the recorded description, which were 21%). Nearly 50% of all GSFC connector faults/failures were caused by workmanship errors. Design caused 16%, failure

to follow process or procedures or insufficient or erroneous paperwork (e.g., no certificate of compliance) accounted for 16%, and human factors were at 1%. Faults/failures caused by connector manufacturer (CMfr) error or non-compliance accounted for 15%; of those manufacturer-caused events, 26% were dimensional defects (i.e., out of specification), and 74% were associated with manufacturer process or workmanship issues (plating, incorrect or missing parts, or other manufacturing-caused defects).

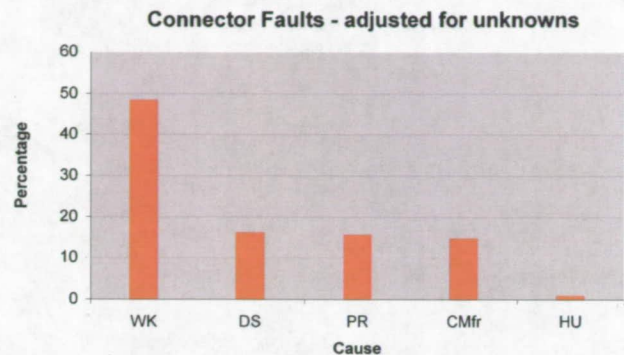


Figure 6. GSFC Connector Faults/Failures by Cause

WK-Workmanship; DS-Design, PR-Procedure
 CMfr – Connector Manufacturer, and HU-Human Factor.

Other classifications were "extrinsic" or "intrinsic;" where the reported component faults/failures were caused by a defect in the component itself (*intrinsic*) or by some external factor, such as an assembly or integration and test process or procedure error, design error, misapplication, or human factor causing the fault or failure (*extrinsic*). Only 19% of connector faults/failures were caused by a defective component (connector or wire); and 81% were caused by extrinsic factors.

GSFC Data Review Summary:

- Approximately 700 connector faults or failures were reported during 1999 to 2008.
- No connector fault or failure caused a satellite or ground system operational failure.
- Most connector faults/failures occurred during fabrication and testing, prior to launch.
- Nearly two-thirds (64%) of all GSFC connector problems, faults, and failures were caused by workmanship and process/procedural issues.
- The five most frequently occurring connector failure modes were: missing or incorrect hardware (16%), damaged or failed (11%), loose (9%), incorrectly wired (9%), not seated or mis-mated - including recessed sockets or pins (8%). Approximately 5% of GSFC

connector faults/failures involved either corrosion or contamination and approximately 3% were related to bent pins.

- Intermittent electrical faults/failures occurred in 20% of the electrical faults/failures.
- Connector problems, faults, and failures have been increasing at a greater rate, particularly during most of 2002 and the last half of 2006, until November 2008.

The system with the most extensive history of space flight is the Space Shuttle fleet; maintained and launched from KSC. The shuttle program has been in operation since 1981 and has completed over 127 space missions. Over this period there have been five Orbiters with two lost (one during the launch phase and the other during ascent). In supporting the NESC connector selection study, KSC mined connector anomalies from the parts database on the Space Shuttle. The data collected was from 1975 (includes test missions) to present and includes all elements in the Space Shuttle Program (SSP). Problem reports specific to connectors and terminations were reviewed for the Orbiters over this period and are summarized in Figures 7A and 7B.

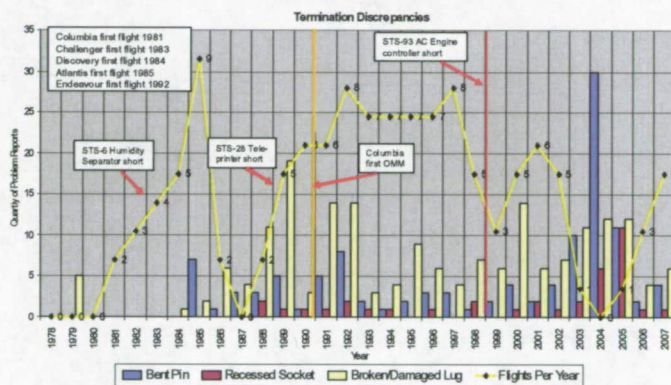


Figure 7A. Orbiter Termination Discrepancies Summary 1976 to Present

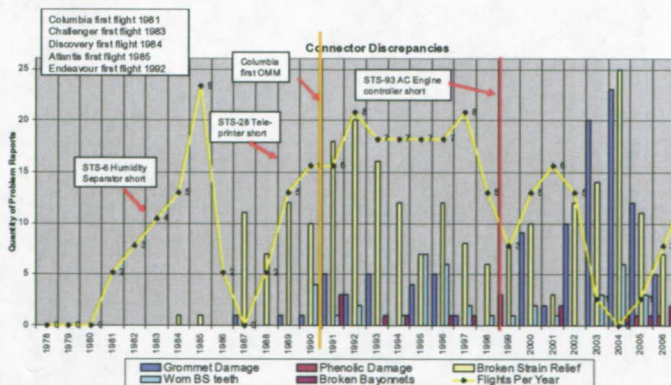


Figure 7B. Orbiter Connector Discrepancies Summary 1976 to Present

A portion of KSC connector discrepancies and faults were compiled and classified according to cause and failure mode in Figures 8 and 9. Thirty three percent of KSC connector discrepancies were attributed to connector manufacturer defects, 20% to workmanship and 16% to "process/procedure" (many of these later were associated with lot traceability and paperwork issues). No design causes were noted, consistent with the Program's mature life cycle.

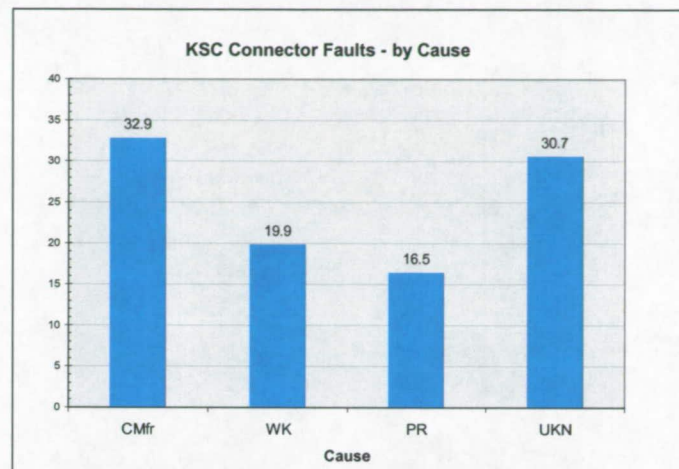


Figure 8. KSC Connector Anomalies by Cause (CMfr- Connector Manufacturer), WK- Workmanship, PR- Process/procedure discrepancy, and UKN- Unknown.

The most frequent connector failure modes were grommet defects (17.6%), damaged or failed connectors (17.2%), missing or incorrect connector parts (14.1%), loose connectors and associated fastening hardware (10.6%), unseated or mis-mated connectors and recessed pins or sockets (8.4%), and corrosion or contamination (8.4%).

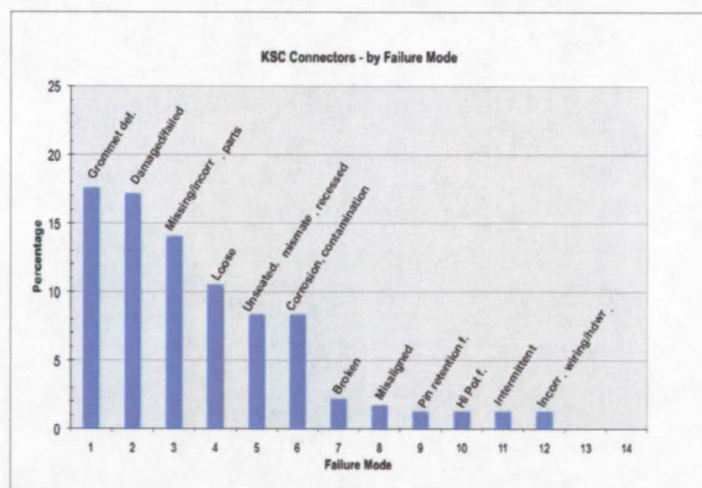


Figure 9. KSC Connector Anomalies by Failure Mode.

Throughout the 29 years of service, there have been significant types of connector anomalies observed that can be summarized as follows, not in any particular order:

- Torn connector grommets
- Wrong size wavy washer installed
- Elongated/double bayonet holes
- Connector threaded body sharp edges damaging wires
- Silicon contamination on pins
- Missing and damaged RFI springs
- Missing and damaged bayonet pins
- Sheared dog-ear locking tab causing loose back shell
- Sheared and damaged insert locking tab
- Feed-through connector inserts 180 degrees off
- Terminal marking off for symmetrical insert arrangement
- Oversized rear grommets/loose back shell
- Marginal insert block bonding
- Missing or damaged retention clips
- Wrong interfacial seal installed
- Nick or cracked interfacial seal
- Bent pins
- Recessed sockets and/or pins
- Miss-pin or cross wired connector

The five most significant anomalies were errors during connector fabrication/build due to a combination of workmanship, inadequate process controls, and application. Some recent examples of the anomalies are (not in any particular order):

- Bulkhead feed-through connector inserts 180 degrees off - causing bent pins and opens
- Wing feed-through connector contamination causing intermittencies
- Wrong wavy washer on connector Savers causing loose connector mating and replacement
- Torn connector grommets requiring connector replacement
- Oversized rear grommets and caused loose back shells
- Umbilical connector data loss due to pin corrosion and contamination
- Missing or partial installed connector snap ring insert retention

For the wing feed-through connector the failure mode was intermittent data drop-out of the wing feed-through a MIL-C-

38999 series 2 connector. The root cause was silicone contamination on the feed-through connector pins and sockets. The silicone contamination created a high resistance, resulting in an intermittent condition (Figure 10).

Consequently, a GIDEP Alert was generated. The connector vendor confirmed the origin of the silicone to be a result of a silicone bath the feed-through connectors were exposed to during manufacturing. Corrective actions were to add a spray bonded interfacial seal process and require a continuity check prior to use.

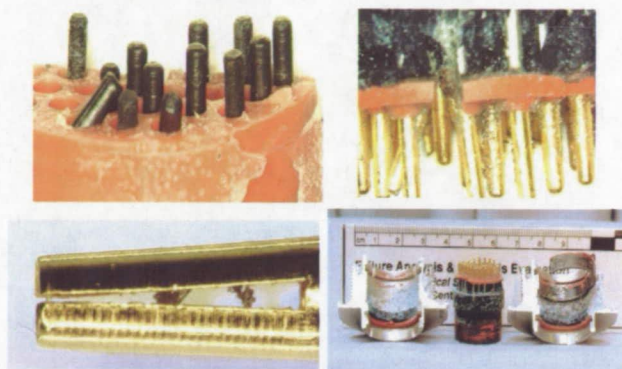


Figure 10. Wing Feed-through Connector Contamination

Numerous connectors have exhibited grommet damage during contact extraction/insertion, which requires connector replacement (Figure 11). Preliminary analysis found several possible causes including seal gland design, grommet elasticity, grommet hardness, and grommet material. Limiting reuse of connector extraction tools is also expected to reduce grommet damage.

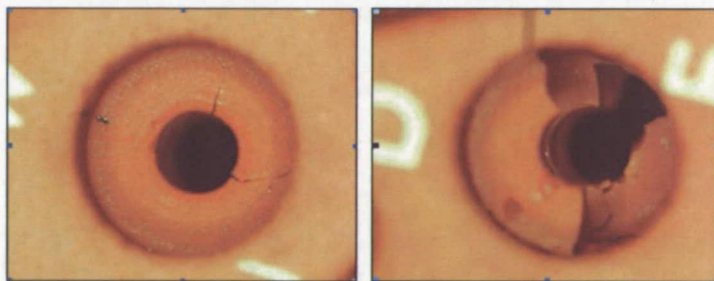


Figure 11. Torn grommet seal examples

Analysis shows that the sharper seal design, coupled with the lower elasticity of the material may be responsible for the poor performance of the middle grommet design (see Figure 12). This grommet design was also most likely to tear during insertion and extraction of contacts.

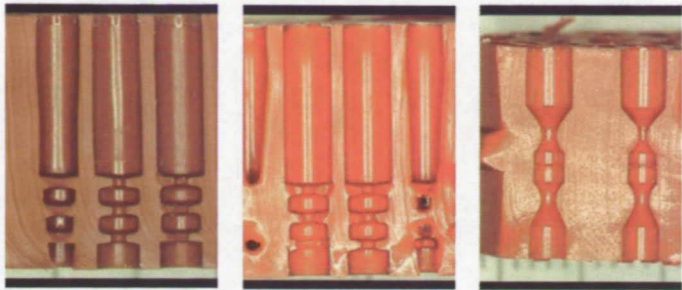


Figure 12. Cross-sections of three manufacturer's grommet seals. The middle design was most likely to tear

Four recent shuttle launches have been "scrubbed" on launch day after the main Engine Cut-Off (ECO) sensor produced anomalous readings; the last failure being in December 2007. The sensor system is one of several that protect the shuttle's main engines by triggering their shut down in the event fuel - either liquid hydrogen or liquid oxygen - levels in the external tank run low. When the fuel level drops below a sensor, the sensor resistance increases and the orbiter's computer reports the tank is "dry". Orbiter computers poll these sensors about every 10 seconds prior to planned Main Engine Cutoff which is about eight and half minutes after launch. If two of the four ECOs indicate "dry" the space shuttle main engines will immediately shut down. If the main engines are shut down prior to normal operating time, it could affect whether or not the shuttle reaches the appropriate orbit.

The sensor system that has experienced anomalous readings is the Liquid Hydrogen (LH2) section of the External Tank (ET). The failure could be the sensors, the wiring harness, one of several connectors or in the avionics box which monitors the sensor resistances. Resistance of the sensors is monitored through the wiring and connectors. The avionics sensor box in the orbiter sends data signals to the orbiter's onboard computer system. Sensor wires pass through a feed through connector in the side of the tank. The external cables run up the external tank vertical strut to the LH2 ET/Orbiter interface. There are four ECO sensors in the LH2 tank; mounted approximately four feet from the bottom of the tank. Similar ECO sensors are also located on the liquid oxygen tank. A schematic of the system is given in Figure 13.

Once propellant loading begins, the LH2 ECO sensors will read 'wet,' indicating they are covered with cryogenic propellant. The sensors are monitored during tanking operations. During the December 2007 launch attempt two of the four LH2 tank ECO sensors gave false readings. NASA's launch commit criteria require three of the four sensors to be functional in order to lift off. A third sensor failed after the tank was drained of fuel. Within several hours of the tanking operation, all four ECO circuits returned correct readings.

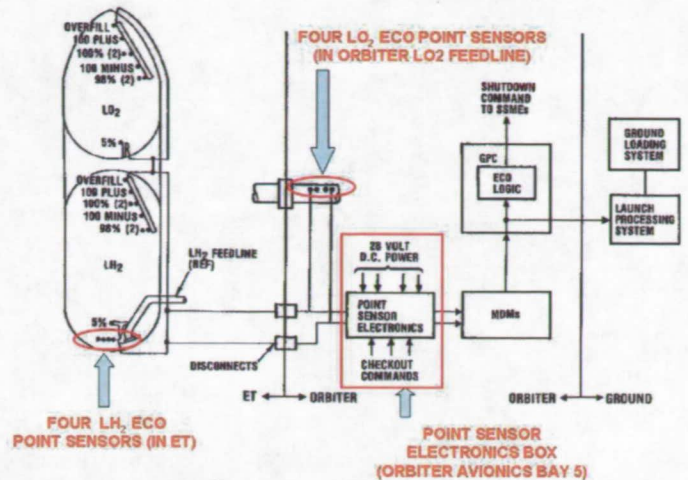


Figure 13. Overall schematic of the Engine Cutoff (ECO) system. The problem was isolated to the liquid hydrogen feed-through connector.

When immersed in LH2 the sensor is "wet" and has a low resistance. Resistance at the avionics box includes the wiring and a "wet" sensor reading would be about 14 ohms. The sensor is "dry" when not immersed in LH2 and reads above 50 ohms at the avionics box. The anomalous condition prior to several shuttle launches was a "dry" reading when the LH2 tank was full. This indicates the sensor had failed open or there was an open in the wiring system. During the investigation of the unsuccessful Dec 2007 launch attempt the avionics box was ruled out as the source of the failure. Extensive fault isolation and ground testing confirmed the open occurred at the LH2 external tank feed-through connector (see Figure 14).

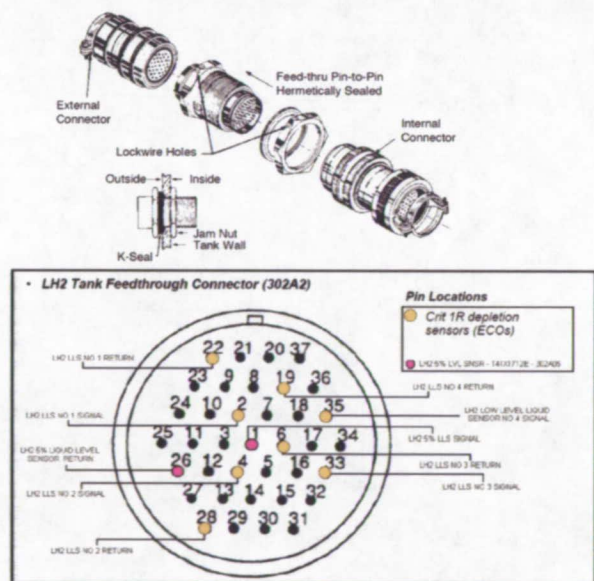


Figure 14. ET Liquid Hydrogen Cryogenic Feed-through

and Mating Connectors and Pin Assignments

Ground testing also revealed the pin and socket contacts would electrically open when the assembly was exposed to LH2. LH2 is approximately -423°F (-253°C) which is well below the operating capability of most materials. Removing the LH2 allowed the connector to warm up and continuity was re-established between the pin and socket contacts. Materials analysis revealed non-conductive contamination on the pin and sockets in the form of a grease and silicone oil (see Figure 15). It is also theorized that lateral pin movement occurs when the connector is exposed to LH2; reducing the contact area between the socket and pin. The failure cause was a combination of events; foremost being the feed-through connector was not designed to withstand LH2 cryogenic temperatures. Testing showed that a thin layer of frozen air/moisture forms on the pin/socket interfaces and pin movement occurs when the connector is exposed to LH2 (see Figure 15). Several years earlier the socket contact was also changed from a four tine to a two tine design. This made the socket/pin connection more susceptible to an open condition. In addition, non-conductive contamination reached the pins and sockets. Silicon oil contamination was most likely introduced during the connector manufacturing process and Krytox[®] grease contamination during a procedure that applied grease to connector faces to improve the seal between the interfaces (Figure 15).



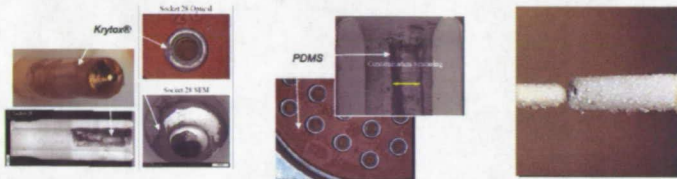
Figure 16. External tank feed-through connector soldered terminations

Connector Survey Results

As part of this assessment, a survey was sent out to members of the AE-8C1 connector committee regarding connector failure modes and questions relevant to selecting space grade connectors. A total of thirteen responses were received. They included some of the largest aerospace connector suppliers and aerospace OEMs. The following is a summary of the general focus of the responses: Vendors and OEMs listed their top connector-related issues which in order of occurrence were contact retention, plating issues, worn-out or damaged coupling mechanisms, bent pins, contact crimp barrel cracking and torn seals. In addition to these common themes responses included issues with markings, dimensional errors on the build, contact/socket damage (handling), manufacturing defects and customer misapplication and mishandling.

Feedback of connector-related issues was most often accomplished through returns and direct customer contact. Very few responses listed any other significant means to feedback field issues; suggesting there might be limited information exchange with connector manufacturers related to field issues. From the aerospace prime contractors, several referenced certification and internal lessons learned databases. GIDEP use was referred to in at least one case for "extreme or systemic cases".

Regarding intermittencies and signal discontinuities, the majority of the responses suggested these occurred but most did not provide specific cases. Many suppliers performed discontinuity testing under a vibration environment that can result in signal drop-outs or opens. Interestingly, at least two of the connector manufacturers responded to the question on intermittencies with commentary on specific cases where their product was involved in an intermittent failure. In addition to these intermittency responses, a number of OEMs suggested that 100% testing of pin/contact retention prior to



Krytox[®] grease was found on the pin and socket

Silicone oil was found on the hard insert connector

At LH2 temperatures atmospheric air forms a frozen layer on the socket and pin contacts

Figure 15. Analysis revealed grease and silicone oil contamination on the feed-through connector sockets and pins. At LH2 temperature a frozen layer of air forms; separating the pin and socket and resulting in an open condition.

The solution to eliminating the loss of continuity between the pins/sockets at LH2 temperatures was to solder the pins and sockets (Figure 16). This was successfully used to solve a similar problem on the Delta/Atlas program. There have been no ECO system anomalies since the fix was implemented in the first half of 2008.

final flight mate could reduce the occurrence of intermittencies.

In one of the most interesting responses to the question of intermittencies, a large aerospace prime contractor discouraged NASA's practice of using D-subminiature (D-sub) style connectors. The response effectively states NASA's growing trend in D-Sub use is in many cases a misapplication since requirements often exceed typical D-Sub capabilities. The responses notes the stamped shell with its floating contacts within the insert make it poor selection for most space applications despite its popularity. The suggested correction is the development and/or selection of more robust connectors that are more like typical Mil-Spec offerings, with a more modern high density design capable of meeting today's more stringent physical space requirements.

Another company response suggested intermittencies can be caused by connector contacts not completely engaging. They specifically gave an example of using a bayonet type coupling with a large wire bundle that can partially pull apart contacts causing intermittency during vibration. Contact fretting corrosion (contact movement causes mechanical wear and material transfer at the surface, often followed by oxidation) or chattering during vibration were the most commonly suggested causes of "cannot duplicate" intermittency failures according to the manufacturers.

Almost all companies recommended using electroless nickel plating for space grade connectors, indicating that it was a good compromise between design needs and cost from a supplier perspective. It was acknowledged that the choice of electroless nickel could be affected by design limitations such as surface conductivity, corrosion resistance, and **Restriction of Hazardous Substances** (RoHS) compliance. Still, a number of companies suggested gold plating for higher conductivity, better EMI characteristics, and design compliance for space applications. Several OEMs noted electroless nickel is not appropriate for aircraft that are exposed to high humidity and salt water environments.

Other companies recommended special handling and manufacturing procedures for electroless nickel. These included controlling surface condition of components and cleaning prior to coating/plating, ensuring the coating/plating is uniform, free of pits, rigorous control of deposition process and elimination of contaminants, use of low sheen types of coating/plating, and protecting against nicking or chipping of finishes.

Most companies acknowledged the need to maintain a life time 2.5 milliohm resistance between connector shells. Suggestions for maintaining a good bonding interface included cleaning surfaces and using the same plating at the interfaces, using low fluorine cross-linked ETFE wiring and using gold-plated connector shells and mounting surfaces.

In general, many vendors stated they offered a number of RoHS-compliant alternatives but one of the largest suppliers

noted in their response that recent discussion of eliminating nickel as a potential heavy metal contaminate presents significant challenges. RoHS compliant plating systems suggested included gold, zinc-nickel, Teflon®-nickel, pure aluminum, zinc-cobalt, and Alumiplate®. Several referenced the latest connector specification MIL-DTL-38999K that includes a number the above-mentioned RoHS compliant plating systems. It was mentioned that while pure aluminum finishes have good corrosion resistance, they do exhibit poor wear durability from galling.

The industry was asked how NASA should communicate its connector requirements to manufacturers. Most responses emphasized tailoring existing standards through close communication with connector vendor application engineering groups. The most common response was that NASA should participate more fully in standards committees such as SAE and ARINC and tailor these specifications for space applications. A common theme in the responses noted that the industry is familiar with military and industry standards and these should be used with NASA-specific modifications.

Qualification by a third party lab prior to procurement for space grade parts was also common in a number of responses. One company stated that ordering space grade parts based on a company's specification sheet can result in receiving connectors that won't meet NASA out-gassing requirements. Another response suggested COTS connectors should be used only in benign and non-critical (i.e., low risk) areas.

In one response, the submitter noted out-of-date qualified parts lists and suggested NASA modernize their parts plans with more current designs. The responder notes that the industry has advanced technologies in the connector arena but are "hamstrung by outdated sets of standards" from their NASA customer.

Regarding composite connectors, three vendors offered part numbers for composite connectors in their lineup and a small number noted their parts were deployed in military aerospace applications. One vendor indicated they expected European Space Agency qualification for their composite connector by fall 2009. Most advised that composite connectors should not be used in areas requiring high strength and/or extreme temperatures and suggested other notably heavier alternatives.

On cryogenic connector offerings, most responses offered no off-the-shelf connector but several noted they had supplied cryogenic connectors on a custom basis. Interestingly, the vendor who supplied the Shuttle ET feed-through connector stated that NASA had misapplied that connector in its (NASA's) cryogenic application. Further, that vendor, as well as a number of others pointed out that few if any connector makers have the ability to qualify their parts in the cryogenic environment beyond liquid nitrogen temperatures. One vendor suggests Elastomeric (silicone rubber) and

polymer materials for use above 200°C, or below -65°C, as a potential candidate for cryogenic applications.

Top NASA Center Connector Issues

Each NASA Center was requested to report the most common and high impact connector-related issues they experience. Reports were received from KSC, JSC, MFSC, GSFC LaRC, JPL and the NASA Lessons Learned Database. The following illustrates common themes and when possible, system examples of failures are provided and possible approaches to mitigate the failures. Issues are not ranked in order since not enough information was available to differentiate between the types of failures that were recorded.

Shorted/bent contact pins or mis-mating were both reported by GSFC, KSC, JSC, the NASA Lesson Learned Database, and by industry responders to the connector questionnaire. This is one of the most serious failure conditions since it can lead to shorting and arcing when sufficient electrical power is available. Causes were due to improper installation by technicians (workmanship) and connector manufacturing defects where mated connector halves were misaligned. This failure condition was noted on several Space Shuttle bulkhead feed-through connectors (MIL-C-38999); failing continuity as a result of bent or crushed pins. The cause was improperly installed connector faces that were 180 degrees out of alignment. The corrective action was for the connector vendor to correct their manufacturing process and include a 100% continuity check. In addition KSC now performs continuity prior to wire harness installation. Bent pins have also been caused by mis-mating connectors. This can be addressed by using scoop-proof connectors. This type of connector has the pins recessed so that when mating a connector it is aligned so the contact pins properly enter the appropriate sockets.

Contact pin/socket contamination leading to open or intermittencies were reported by GSFC, KSC, JSC, MFSC, and the NASA Lesson Learned Database. Typically, contamination is attributed to silicone oil, a thin film build-up or a corrosion product. In some cases inadequate contact wiping action and retention was also noted. This failure condition typically occurs on multiple connections. An example of contamination is intermittent data drop-out of the wing feed-through connector (40M38277, NASA specification for circular space grade connectors) on the Space Shuttle. The root cause was silicone contamination on connector pin and sockets creating a high resistance and intermittency. A continuity check was added prior to connector use. Contamination on contact pins and sockets was also a factor in a recent Space Shuttle launch scrub-related to an external tank feed-through connector.

Connector plating corrosion or corrosion on connector components was reported by GSFC, JSC, MFSC, LaRC, and the connector questionnaire responders. Corrosion has led to loss of connector shell electrical bonding (EMI shielding) or

electrical failures from the corrosion products shorting connector pins. This typically affects multiple connections and connectors. Several instances of connector corrosion were provided by GSFC that affected several satellite systems. In each case a high resistance bonding measurement was reported. One cause has been attributed to out-gassing of a corrosive compound from fluoropolymer wire insulation and damaged electroless nickel coating on aluminum connector shells. These issues can be addressed by avoiding damage to the electroless nickel coating and using low out-gassing wire insulations.

Low or inadequate contact pin retention forces were reported by GSFC, KSC, JSC, the NASA Lessons Learned Database and connector questionnaire responders. This typically impacted multiple connectors and created intermittencies. An example reported by GSFC affected a number of non-NASA satellite systems using the GSFC G08 style connector contact sockets (a tailored version of MIL-C-39029). The failure modes were electrical opens and intermittencies; the root cause was attributed to improper annealing of the contact socket material and oversized boring of sockets. Marginal sockets were identified by conducting retention tests. GSFC systems potentially affected required 100 percent screening for pin retention of GSFC's entire inventory showed no failures. Several OEMs also suggested 100% pin/contact retention testing prior to final flight mate to reduce intermittency occurrences. It is, however, more cost effective to perform a receiving pin retention screen because inspecting prior to final mate becomes a significant cost (and schedule) driver and some connectors may not be accessible. The receiving screen will be sufficient only if proper connector handling protocols are implemented to avoid subsequent damage during integration and testing.

Contact crimp failures were reported by KSC, MSFC, the NASA Lessons Learned Database, and connector questionnaire responders. As an example, MSFC reported a group of electrical contacts built to the MSFC connector specification 40M38277 (NASA circular space grade connector) failed the crimp tensile test. Pull testing and other crimp integrity tests such as ultrasonic inspection have been found effective in identifying marginally crimped contacts.

Unmated connectors and mis-wiring due to workmanship errors during installation or maintenance was reported by GSFC, KSC, LaRC and the NASA Lessons Learned Database. The NASA Lessons Learned Database contained several write-ups of connectors that were unmated or improperly mated due to a workmanship error. One example reported that after a launch, it was determined that a connector was not mated since an instrument was running hotter than normal. Connector mating verification was recommended. Using connectors with a visible mating and tactile indicator should also be considered.

Loose connectors due to manufacturing defects such as a wavy washer and worn bayonet retention have been reported

by GSFC, KSC, LaRC, the NASA Lessons Learned Database, and the connector questionnaire responders. A demated connector has also been attributed to connector manufacturing defects and worn engagement mechanisms. An example of this failure condition was a Space Shuttle connector saver that lost detent when axial force was applied and resulted in subsequent low detent/de-mates torque forces. Root cause was determined to be improper heat treating and the dimensional structure of the wavy washer that maintains engagement pressure. One solution is to use the series 3 style MIL-DLA-38999 connectors which have a more robust coupling mechanism.

Damaged connector elastomeric seals were reported by KSC and the connector questionnaire responders. KSC has reported numerous connectors have had grommet damage during extraction and insertion, which required replacement. The root cause has been attributed to several conditions including seal gland design, dimensions out of specification, grommet elasticity, a grommet hardness, and grommet material. Replacing the tools more often or a redesign of the extraction tools is another consideration for reducing grommet damage.

A cryogenic connector failure was reported by MSFC and the NASA Lessons Learned Database. The cryogenic related connector failure example from MSFC caused four launch scrubs of recent Space Shuttle missions. Root cause was isolated to the external tank feed-through connector. The connector socket and contact lost connection due to the sockets/pins containing non-conductive contamination and the sockets moving relative to the pins at cryogenic temperatures.

III. CONCLUSION

Considering the large quantity and wide variety of connectors successfully flown on human and robotic space applications, the number of operational failures is quite low. However, "high profile" failures with significant cost, schedule, safety, and/or mission success impacts continue to occur (e.g., Shuttle ET ECO feed-through connector). Connector failures can affect multiple systems and may compromise system redundancy. Further, certain connector problems have continued to reoccur (e.g. contamination issues). Analysis of failure data also shows that the rate of connector problem occurrence is not decreasing over time.

Connector failures occur throughout their life-cycle (design to field usage). Analysis on a data sample suggests that the majority of connector issues are caused by factors such as process or procedure errors, design, misapplication or human factors, rather than component intrinsic defects. Selecting a specific connector impacts multiple subsystems (e.g., mechanical, electrical, wiring) and systems engineering (redundancy and system performance), as well as sustaining engineering (e.g., installation, maintenance, ground operations, etc.). It is not evident that the connector selection

process adequately considers all subsystems and functions impacted. Nonetheless a significant number of failures (~64% from one data set) are not caused by the selection process. Manufacturing deficiencies and workmanship errors during installation caused the majority of these failures.

The GIDEP database, while beneficial, gives limited information and provides an incomplete picture of connector issues. However, as manufacturers are often encouraged to write GIDEPs on their own products, the results often include positive "spins" and usually omit details that could provide competitive advantages to other vendors. Further, NASA, and many of its contractors, use internal alert systems that are generally access-restricted and thus, the information does not become widely known. NASA and Contractors are required to verify connector selection against GIDEP issues and submit issues to GIDEP; however, submitting issues to GIDEP is not enforced.

Electroless nickel connector plating has experienced corrosion and flaking problems in aviation applications exacerbated by time, environment, and/or handling-induced damage. Electroless nickel connectors can perform well in space applications with appropriate cautions (i.e., ISS). Gold-plated aluminum connectors with a nickel barrier should be used when there are stringent EMI shielding requirements or for an extended exposure in atmospheric conditions. Electroless nickel aluminum connector performance and specifically corrosion resistance can be improved by using enhanced manufacturing processes and appropriate handling.

Funding support for NASA space grade connector specifications and qualified supplier lists is inadequate to keep them current. Under Acquisition Reform (since 1994), many military specifications that NASA uses (including many connector type documents) have been cancelled and/or converted to industry documents (e.g. SAE, ASTM, NEMA, IPC, IEEE, etc.) leaving the user projects responsible for oversight. Critical quality and reliability decisions are being made by the responsible committees (i.e. SAE, ASTM, and NEMA), but NASA has lacked consistent participation in these committees. A review of two NASA connector specifications revealed many of the cited military and government specifications had been cancelled and converted to industry documents.

NASA's connector problem experiences have been characterized into a list of top connector issues. Issues were selected based on anecdotal evidence of system impacts and commonality between Centers. The top issues are listed below in no particular rank order:

- Electrically shorted, bent and/or recessed contact pins.
- Contact pin/socket contamination leading to open or intermittencies.

- Connector plating corrosion or corrosion of connector components.
- Low or inadequate contact pin retention forces.
- Contact crimp failures.
- Unmated connectors and mis-wiring during installation or maintenance.
- Loose connectors due to manufacturing defects such as wavy washer and worn bayonet retention.
- Damaged connector elastomeric seals.
- Cryogenic connector failure.

Recommendations for improving connector selection, reliability and overall integrity were provided to the NASA Office of Chief Engineers. A summary is given below:

- NASA Centers should review existing NASA specifications, update active ones, cancel inactive and un-maintained ones, and remove references to cancelled specifications.
- NASA Engineering organizations should investigate alternative connector shell plating systems and materials for space use. Several new connector shell materials are now available, which are RoHS compliant and offer improved performance over conventional connector shell materials.
- NASA Engineering organizations should include a systems engineering review of electrical connectors during spacecraft design and development phases. The systems engineering review should include (but not be limited to): system redundancy, cross discipline impacts, connector life cycle analysis, and human-system integration analysis (including connector manufacturability, operability, and maintainability considering the workers and their work environments). Systems engineering organizations should thoroughly review all Commercial Off the Shelf (COTS) electrical connector applications.
- Form a NASA wiring systems working group and more fully participate in the established Government Interagency wiring system working groups and SAE committees, specifically SAE AE-8A and AE-8C.

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Author Biographies:



Dr. Chris Iannello began his career with NASA in 1989 as an intern in Ground Power Systems. After obtaining his Bachelor of Science in Electrical Engineering (BSEE) in 1994, he began full-time work as a NASA systems engineer focusing on both power and facility control/monitoring systems. In 1998, Dr. Iannello's fellowship award allowed him to attend the University of Central Florida to pursue a doctorate in Electrical Engineering which focused on power electronics and involved both R&D and teaching at the graduate level. After his return from academia, Dr. Iannello, served as a key team member in developing the Kennedy Space Center's (KSC) basewide control system and developed and served as the project manager and engineer on a series energy/controls projects which became the largest in the history of the KSC saving in excess of \$6 million annually. After completing these projects, Dr. Iannello was tasked with the analysis and simulation of a number of NASA most significant electronics issues including the Shuttle Engine Cutoff Sensor Avionics, the Hubble SM4 Power System Redesign, the Master Event Controller Spurious Output, and ISS Power Shutdown anomaly, as well as others. In 2007, Dr. Iannello joined the Chief Engineer's Office as an Assistant to the Vehicle Processing Chief Engineer. In 2008, Dr. Iannello was also named the Deputy Power Technical Fellow by the NASA Engineering and Safety Center (NESC). In 2009, his role in the Chief Engineer's Office was expanded and he now serves as the Deputy Chief Engineer for Ares, the senior technical position at the KSC for NASA's new manned rocket. He continues to work as a consultant on power electronics issues, is an invited session chair to the Institute of Electrical and Electronics Engineers (IEEE) Power Electronics conference, and has published over 20 publications in IEEE Conferences and Journals.

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George is currently working as an independent consultant and is a member of the NASA Engineering and Safety Center Power and Avionics Teams. He is also retained as a subject matter expert by the Naval Air Systems Command Wiring System Branch and Air Force Research Laboratory Electronic Materials Evaluation Group. He is a member of SAE AE-8A, AE-8C, and AE-8D committees. George is married with two daughters and lives in Dayton, OH.